Time-Dependent Predictions of the Ambient Solar Wind Using the Zeus-3D MHD Code

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LONG-TERM GOALS

To improve the prediction of traveling solar disturbances which impact the geospace environment. Such disturbances, which are associated with both coronal holes and coronal mass ejections (CMEs) launched from the Sun, can cause substantial geomagnetic effects, including the crippling of satellites, disruption of radio communications, and damage to electric power grids.

OBJECTIVES

To improve significantly the modeling of the solar wind flow from the outer corona to Earth (i.e., from ~0.1 to 1AU) by incorporating the Zeus-3D magnetohydrodynamic (MHD) code [*Stone and Norman*, 1992a,b] into NOAA/SEC's Wang-Sheeley-Arge (WSA) ambient solar wind prediction scheme. Use of the Zeus-3D code will permit routine, quantitative predictions of key solar wind parameters (vector velocity and magnetic field, density, and temperature) near Earth, which are critical for accurate prediction of the magnetospheric state. It will also allow the time-varying ambient solar wind structure to be taken into account, which is particularly important near solar maximum. This will be a substantial improvement over the WSA's current capabilities, which include only wind speed and interplanetary magnetic field (IMF) polarity and which neglects explicit time-dependent changes.

APPROACH

The original Wang and Sheeley (WS) model [*Wang et al.*, 1992], a combined empirical and physics-based representation of the quasi-steady global solar wind flow, is a product of research efforts at the Naval Research Laboratory. It predicts ambient solar wind speed and IMF polarity at Earth and is thus useful for forecasting recurrent interplanetary disturbances. The NOAA/SEC implementation of the model (i.e., Wang-Sheeley-Arge) serves two purposes with respect to space weather forecasting: 1) it provides advance warning of high-speed solar wind streams, which are associated with recurrent geomagnetic disturbances and increased high-energy electron fluences near Earth; 2) it provides our best estimate of flow conditions and structures lying in the path of transient disturbances (such as CMEs and magnetic clouds) headed toward Earth. That is, dynamic interactions with intervening structures can have a significant impact upon the propagation speed of CMEs and can significantly influence their physical properties, such as magnetic field intensities and orientations.

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14. ABSTRACT
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Wang-Sheeley-Arge (WSA) is an improved operational version of the original research-based WS model. Over the last few years, a number of modifications have been made to it that has enhanced both its predictive performance and reliability. These include 1) significant improvement in the handling and quality of the photospheric field data used as input to the model; 2) inclusion of an improved upper coronal model that spans the region from 2.5 $R_{\odot} < R < 30\ R_{\odot}$; 3) development of a new and substantially better empirical method for specifying solar wind speed near the sun, which is critical for obtaining accurate predictions at the Earth; 4) inclusion of an ad hoc technique for accounting for stream interactions; and 5) coupling and testing of the coronal part of the model with two different magnetohydrodynamic (MHD) solar wind numerical models: the Han-Detman [*Detman et al.*, 1991] and the Odstrcil ENLIL [*Odstrcil and Pizzo*, 1999a,b] codes. We are now in the process of incorporating the Zeus-3D MHD code into the operational WSA prediction scheme. Zeus-3D was chosen because it is much more sophisticated than the Han-Detman code, but at the same time, substantially less demanding of resources than Odstrcil's ENLIL model.

WORK COMPLETED

Under the advisement of the PI, primary implementation responsibilities for this project have been assumed by Dr. C. N. Arge. Much of the effort spent on the Wang-Sheeley-Arge (WSA) model over the last year has concentrated on three objectives: 1) incorporation of recent improvements made to and extensively tested with the research and development version of the model into the NOAA/SEC operational version, 2) further improvement and testing of the empirical relationship used to specify solar wind speed near the Sun, and 3) incorporation of the Zeus-3D MHD code into WSA.

With the assistance from scientific programmer Leslie Mayer, a number of improvements originally made to the research version of WSA were recently incorporated (after extensive testing) into the NOAA/SEC operational version of the model. These include an improved interpolation technique for both resizing the grid of the photospheric maps and converting them from sine-latitude to latitude (the old technique tended to over-estimate the strength of the polar fields), an improved upper coronal model (i.e., the Schatten Current Sheet (SCS) model [*Schatten*, 1972]) that spans the region from 2.5 $R_{\odot} < R < 5\ R_{\odot}$, and a substantially improved empirical relationship for specifying solar wind speed near the Sun. Figure 1 shows the real-time solar wind speed predictions made by the recently upgraded model over the last 3 Carrington rotations. As seen in the figure, the agreement between predictions and observation is quit good. Further improvements have been made to the NOAA/SEC WSA web page such as the inclusion of daily-updated 2-dimensional (2-D) plots and movies (i.e., in the ecliptic plane) of solar wind speed and IMF polarity (e.g., Figure 2 below). These 2D plots and movies are, temporarily, only available to SEC forecasters and researchers on an internal development page. As soon as the standard SEC internal review of the newly modified WSA web page is completed, they will become available to the general public.

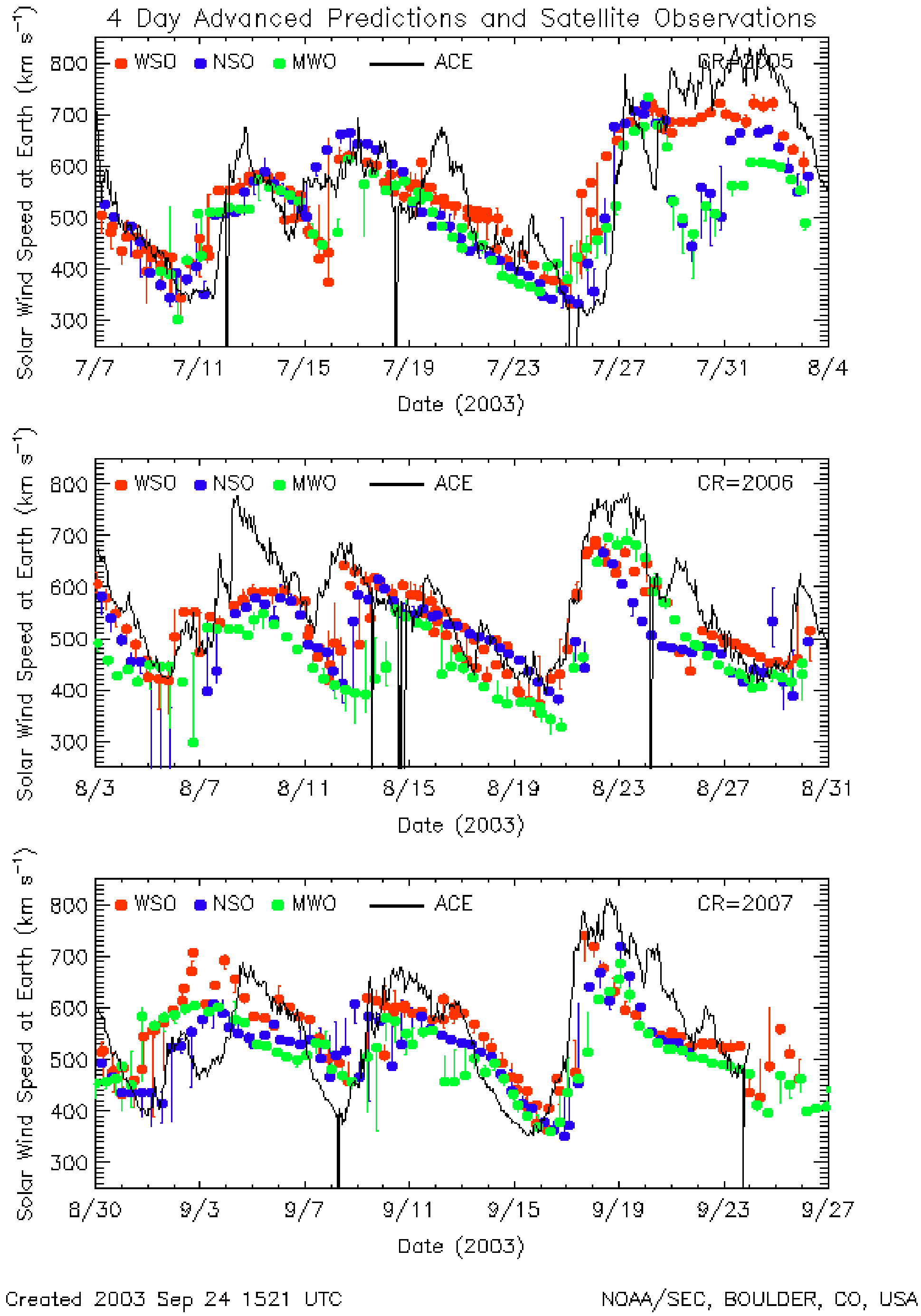

Figure 1. Comparison of real-time ACE solar wind speed data (solid black line) with Wang & Sheeley model predictions (colored dots) for the last three Carrington rotations.
[The three sets of predictions (i.e., red, green, and blue dots) are based on data from, respectively, Wilcox (WSO), Mount Wilson (MWO) and Kitt Peak (NSO) solar observatories. The vertical bars associated with the colored dots are uncertainty estimates of the solar wind speed predictions, which are determined by calculating the predicted solar wind speeds for the expansion factors located 2.5 degrees above and below the sub-earth point.]

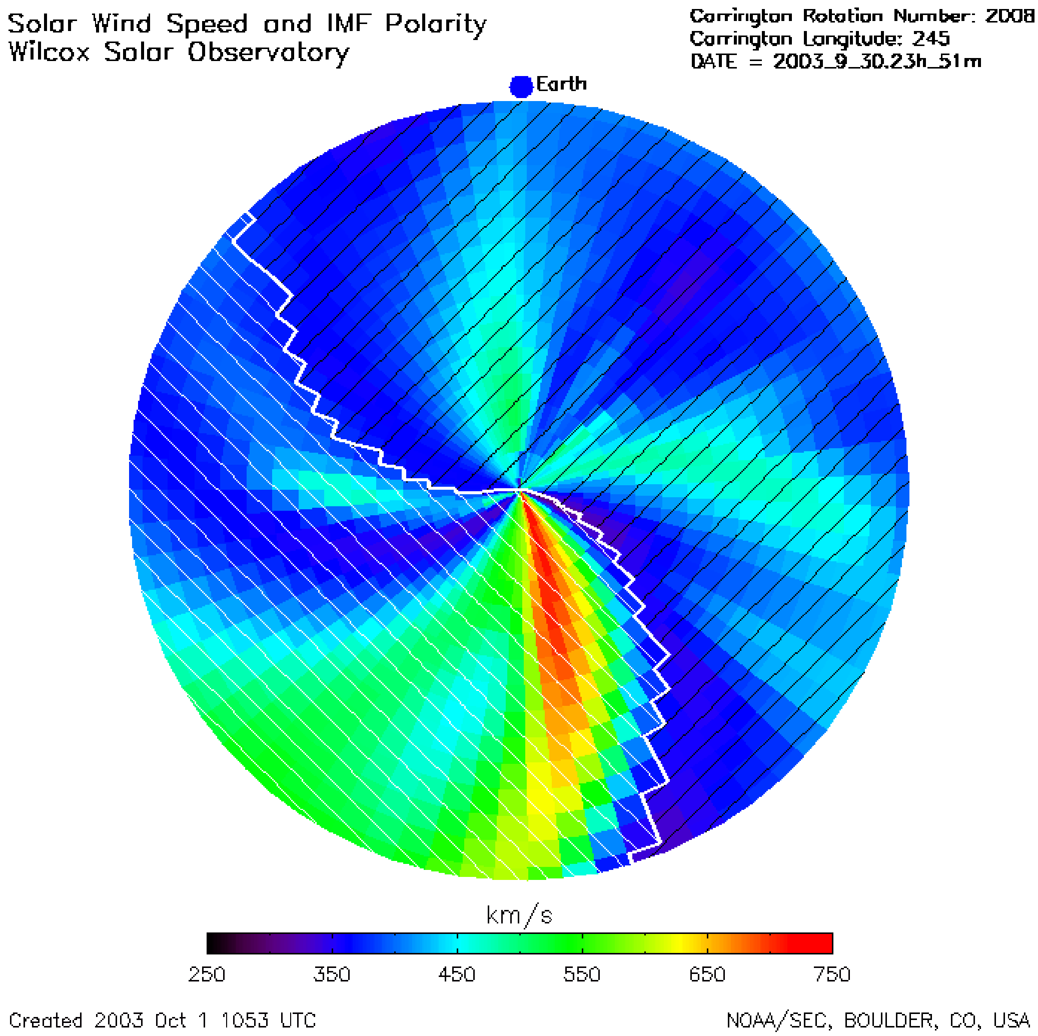

Figure 2. 2-D Solar Wind Speed and IMF Polarity in the Plane of the Ecliptic [Bright red corresponds to high (~750 km s^{-1}) while dark blue to slow (~ 250 km s^{-1}) solar wind speed. Regions filled with white (black) diagonal lines have magnetic field lines directed radially outward (inward) from (toward) the Sun. The Sun is located at the center of the plot while Earth is positioned near top-center.]

As mentioned in last year's report, we have found [*Arge et al.*, 2003] a promising new empirical relationship for specifying solar wind speed near the Sun that is a function of two coronal parameters, flux tube expansion factor (f_s) and the minimum angular separation (at the photosphere) between an open field footpoint and its nearest coronal hole boundary (θ_b). A recent comprehensive 8-year historical verification study using daily updated MWO photospheric maps demonstrates that the new empirical relationship works well over nearly an entire solar cycle. This result is extremely encouraging, since SEC forecasters have informed us that the WSA is of its greatest use to them during the declining and minimum phases of the solar cycle. As we are now just entering the declining phase of the solar cycle, we expect the newly updated model to be used extensively for many years to come.

Because of the extended delay (due to new Department of Commerce grant rules and oversight) in receiving this year's ONR funds, we have not been able to keep to the time table originally specified in our proposal. Nonetheless, we have, with some effort, successfully ported Zeus 3D to a new Linux workstation and tested the code using a standard test problem with good results. The new Linux machine ran this problem 12 times faster than our older HP workstation. This order of magnitude increase in processing speed helps move us toward our objective of having a quick running solar wind model that runs on an inexpensive desktop workstation. To lay the groundwork for incorporating Zeus into WSA, we have been working closely with collaborator Dusan Odstrcil to more fully interface his more advanced 3D MHD ENLIL numerical code with the PFSS+SCS models. For example, the inter-calibration between the PFSS+SCS and ENLIL codes has been significantly improved. We have also generalized the coupled PFSS+SCS model to work with synoptic maps having different grid resolutions. Recent simulations using the combined PFSS+SCS+ENLIL models are very encouraging, as the MHD parameters (i.e., velocity, density, temperature, and field strength) predicted by the combined model are generally in good agreement with observations such as those shown in Figure 3 for Carrington rotation (CR) 1896. In another case, we simulated two different solar wind scenarios for CR1922, in which a well know coronal mass ejection occurred, using the combined PFSS+SCS+ENLIL codes: 1) a standard ambient solar wind case and 2) a simulated transient case representing the May 12th, 1997 CME. In the latter, Odstrcil launched an over pressured hydrodynamic cloud that propagated through the ambient solar wind obtained in the first case. A paper reporting the results of this work is in preparation. These results are very encouraging, as it seems to confirm that good results can been obtained through the coupling of frequently updated static potential field solutions with a time dependent 3D MHD solar wind propagation code.

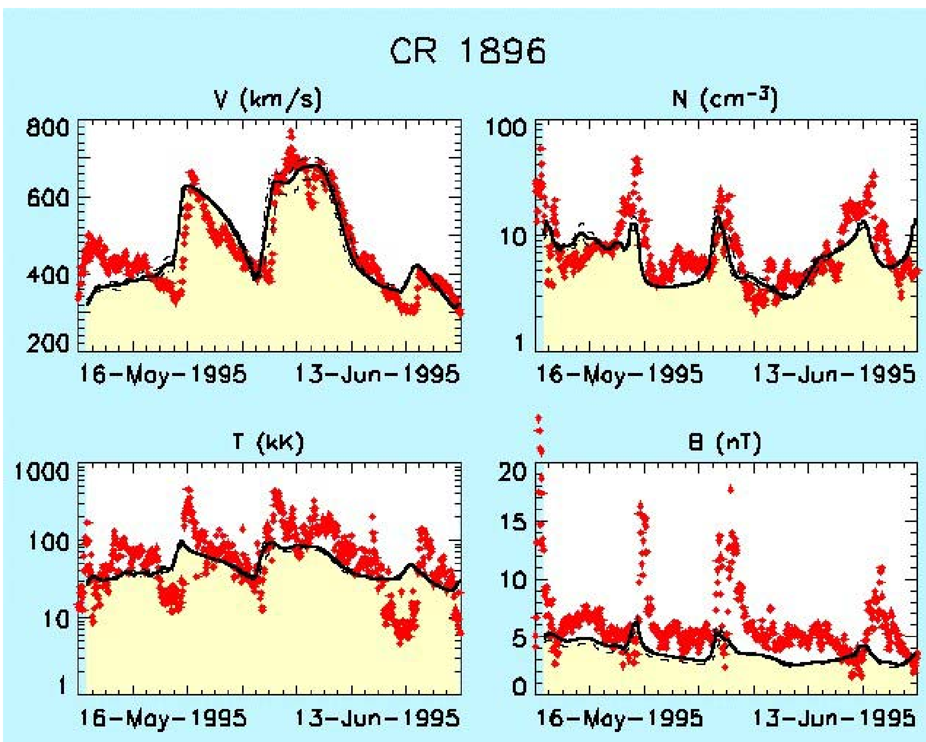

Figure 3. Comparison of simulation results generated by the coupled WSA+ENLIL model with Wind satellite observations for Carrington Rotation 1896.
[Starting in the top left corner and moving clockwise: Speed (V), Density (N), Magnetic Field Magnitude (B), and Temperature (T)]

RESULTS

A number of important improvements were incorporated into SEC's operational WSA model last year that has significantly improved real-time forecasts of solar wind parameters (e.g., see Figure 1). 2D spiral plots and 7-day movies requested by SEC forecasters have recently been added to the SEC WSA page to assist them in making space weather forecasts. We have Zeus-3D working on a new, fast running Linux machine that will significantly reduce, by approximately an order of magnitude, numerical simulation run times. Our work with Odstrcil and his advanced ENLIL solar wind model has confirmed that good results may be obtained through the coupling of the coronal component of WSA with an MHD solar wind model. The experience gained through this collaboration will help us with the coupling of WSA and Zeus-3D.

IMPACT/APPLICATIONS

In addition to direct operational use at NOAA/SEC and other forecast centers, the WSA model continues to enjoy increasing interest and application in the areas of space weather and solar-interplanetary research as well as educational outreach. WSA now plays a fundamental role in the empirical modeling effort of the National Science Foundation's Center for Integrated Space Weather Modeling (CISM). Dr. Arge has taught lectures and labs on WSA at Boston University's two-week Space Weather CISM Summer School for the last three years.

TRANSITIONS

NOAA/SEC forecasters routinely use WSA as a forecasting tool as does the space weather research community. The WSA model has been fully incorporated into the CISM empirical modeling effort. The Scientific Working Group (SWG) panel of the Community Coordinated Modeling Center (CCMC) recommended recently to its steering committee that WSA be included as one of models available there for public use.

RELATED PROJECTS

Dr. Arge is an active participate of Boston University's CISM project. He works closely with researchers at the High Altitude Observatory (HAO) and has the role of liaison scientist between the solar CISM effort and HAO. Dr. Arge is serving on the CCMC's SWG panel for the next two years.

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